Application of Three-Phase Methodology for Retrofit 4.0 in Legacy Industrial Plants

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***Abstract*—This work presents the non-invasive Retrofit 4.0 in a metal-mechanical industry employing the Three-phase Methodology (TpM) for Industrial Internet of Things (IIoT). Retrofitting 4.0 involves integrating legacy industrial machinery into a real-time monitoring environment using a data network, aligning with Industry 4.0 principles. The primary objective of this endeavor is to monitor production performance and anticipate plant enhancements through real-time monitoring of machine operation cycles and Receiver Signal Strength Indicator (RSSI) variations. These variations are tied to the movement of sector operators' quantities. Due to the absence of an online monitoring system, certain production processes suffer from information gaps and reliance on manual production data entry. Using the TpM, a Proof of Concept (PoC) was conducted with two motivations: monitoring machine operating cycles through current sensors and evaluating personnel movement through RSSI. For the PoC implementation, a wireless sensor network was designed for data transmission, without the need to alter the manufacturing processes, ensuring non-invasive monitoring. The results for the operating cycle and operator movement were effective, integrating this industry and its legacy into the IIoT context, enabling a non-invasive Retrofit 4.0 in conjunction with a guiding methodology.**

Keywords- TpM Three-phase Methodology (TpM), Proof of Concept (PoC), Industrial Internet of Things (IIoT), Wireless Sensor Network (WSN), Key Performance Indicator (KPI), Receiver Signal Strength Indicator (RSSI), Computer Numeric Control (CNC).

I. INTRODUCTION

This paper addresses the challenge faced by legacy industries in Brazil and other countries, which cannot fully adopt Industry 4.0 due to the cost and complexity of replacing existing systems with IIoT solutions. In Brazil, there are extensive legacy industrial complexes that are gradually transitioning to Industry 4.0 [13], with a significant need for modernization without replacing the existing infrastructure. Many of these plants are highly efficient and effectively deliver the desired final products or services, but with some hidden production performance data mismatches sometimes, enforcing the needs of an evasive approach in many cases to attend the correct 4.0 transition. Despite meeting their demands, these industries have an underlying need to integrate into IIoT for advantages such as productivity and efficiency. The article proposes the adaptation of the TpM [1] [2] for a non-invasive Retrofit 4.0, aiming to develop an IIoT solution through a Proof of Concept in a metal-mechanical sector company.

The approach focuses on operational improvements without altering any manufacturing processes, highlighting the relevance of IIoT for industrial efficiency. The article presents a structured framework, including conceptual review, proposal, description of the proof of concept, execution steps, results analysis and conclusion, the objective is to emphasize the importance of IIoT in enhancing financial outcomes in modern industries. The case study involves establishing a connection between a legacy sector of an industrial plant and a 4.0 industrial environment.

This connection aims to address two Key Performance Indicators (KPIs): monitoring machine cycles through specific current draw motor values and observing RSSI variations caused by personnel movement that affect signal propagation.

This paper is structured as follows. In Section II, we explain the Three-phase Methodology and the industrial scenario. In Section III, we detail our proposal for methodology chain application in Retrofit 4.0 through PoC. Section IV describes the PoC with TpM chaining and motivations. In Section V, we present the results analysis. We conclude our work in Section VI.

A. Related work

The Industry 4.0 revolution is in full swing, and many traditional industrial facilities are on the path to transformation through Retrofit 4.0. Below are some significant research examples focusing on the modernization of legacy industrial plants.

Article [9] describes the transition from a traditional production line to Industry 4.0 using logical connectors, which function as management interfaces. This retrofit, combining both hardware and software, is invasive and might not be suitable for all industries.

Article [4] highlights the use of energy sensors to monitor KPI´s in traditional CNC machines. This data is wirelessly transmitted and can be monitored in real-time through a mobile app.

Article [10] focuses on monitoring drilling machines, capturing data such as rotation speed and drilling depth. The data is converted into packets and transmitted to an edge device on a wireless sensor network.

II. THE THREE-PHASE METHODOLOGY AND THE INDUSTRIAL SCENARIO CONSIDERED

In this section, we review some concepts related to our proposal. We begin by reviewing TpM as a methodology for

 ISBN: 978-1-68558-089-6

IoT solutions [1] [6]. We adapt this approach to the specific monitoring needs of the industry targeted in the proof of concept. Next, we examine the industry's structure as defined by [5], encompassing the levels of enterprise and factory. This analysis served as a basis for applying TpM to the non-invasive Retrofit 4.0, facilitating the industry's transition to IIoT.

A. *Three-phase Methodology – TpM*

The Three-phase Methodology was created for the development of IoT solutions. However, it is not designed for IIoT and is a generic proposal not directly suitable for Retrofit 4.0. The methodology segments the analysis into three phases:

Phase 1 - Business Consideration: It establishes the fundamentals for a viable IoT solution, detailing the business and identifying needs. A 6-level reference model [8] is adopted, differentiating between streaming and static data [3].

Phase 2 - Requirements Gathering: In this phase, the focus is on collecting requirements for an IoT solution aligned with the business needs. A "top-down" approach is adopted, considering display, abstraction, storage, edge, connectivity, and data acquisition.

Phase 3 - Implementation: In this phase, the IoT solution is implemented, adopting the appropriate technologies to meet the requirements defined in Phase 2. Aspects related to variable analysis, connectivity, edge elements, storage, and the creation of a platform for data display and analysis are addressed.

B. *Industry Structure*

This work proposes an approach that combines a methodology for developing IoT solutions with the industrial structure outlined by [5]. The industrial structure is divided into Enterprise Level, responsible for strategic management, and Factory Level, where production processes and quality control take place, shown in Figure 1.

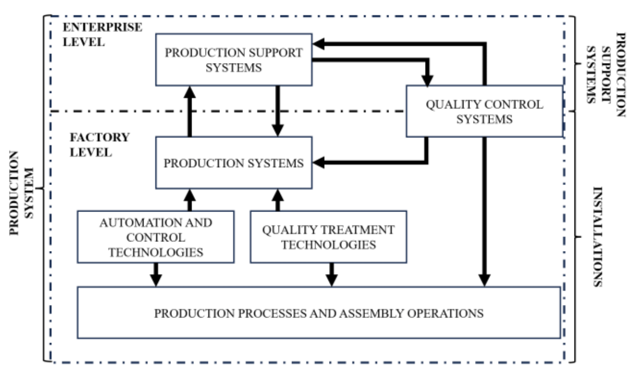

Figure 1. Division of the Production system [5].

The IoT solution aims to drive the efficiency and growth of the company, benefiting it with increased revenues through internal investment, encompassing manufacturing processes and impacting the entire organization.

III. PROPOSAL

This paper proposes a PoC for the application of the TPM to enable an IoT solution through Retrofit 4.0 in industrial environments. The focus is to demonstrate how this approach can enhance revenues at the enterprise level. The combination of the TPM with IoT within the context of Retrofit 4.0 aims to optimize manufacturing operations, improve efficiency, and drive growth in business revenues, the TpM phases are incorporated, and the scalability of this methodology allows for the organized inclusion of new projects. The segmentation of project phases creates a connection with the divisions of the production system defined by [5]. This exemplifies the collaborative utilization of the TPM in deploying Retrofit 4.0 to drive business expansion through IoT.

The segmentation of project phases using the TPM establishes a connection between Figure 1 and the divisions of the production system according to [5], as illustrated in Figure 2.

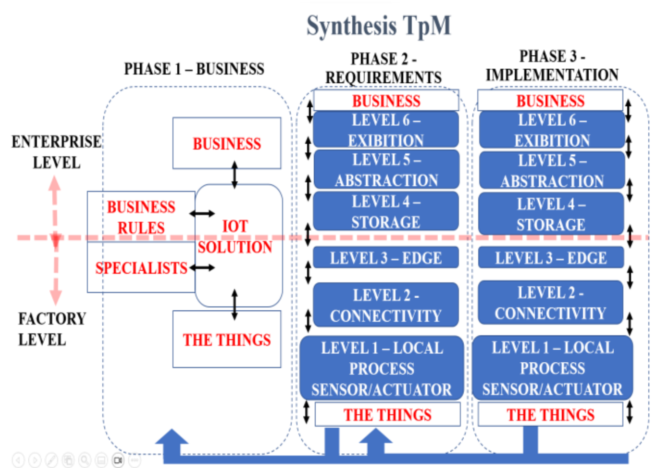

Figure 2. Incorporating TpM project phases into company areas [1].

The proposal for Retrofit 4.0 in the industry combines the concepts of the production system [5], the IoT reference model [3], and the TpM.

In Figure 2, Phase 1 is associated with the enterprise level, along with part of Phases 2 and 3 up to storage at the enterprise level. The remaining portions of Phases 1, 2, and 3 are connected to the factory level, encompassing assets, experts, edge elements, connectivity, sensors, and actuators.

Phase 1 establishes the foundation for Phases 2 and 3 of Retrofit 4.0. The process begins with a business assessment at the enterprise level to determine the feasibility of the IIoT solution, assured by a methodology. Furthermore, the proposal motivates the company to develop scalable IoT solutions over time. With the adoption of Retrofit 4.0, IIoT solutions are created in an organized manner, avoiding isolated approaches within the factory. This guides the industry in effectively crafting IIoT solutions aligned with its overarching goals.

 ISBN: 978-1-68558-089-6

IV. PROOF OF CONCEPT

A. Description of the TpM phases for the PoC

1) PHASE 1 BUSINESS

A survey carried out in the company identified a lack of real-time automatic monitoring in the production line, with the chamfer-grinding department as the focal point. Currently, the control is manual, involving data input into terminals and storage on a server. This leads to gaps in records and a lack of information about events preceding performance drops.

a) Motivation

The initial motivations are twofold:

1- To monitor the performance of a machine within the sector.
2- To conduct real-time monitoring of operator's movement within the same sector [7].

Motivation 1: To monitor the current values of an AC motor in a machine, focusing on KPIs such as "machine in cycle" and "machine stopped."

Motivation 2: To implement a wireless sensor network to measure operator's movement through radio signal variations within the sector during different shifts.

The study proposes the establishment of a wireless sensor network with multiple strategically positioned links across the factory floor. The objective is to monitor variations in movement through RSSI and install a current sensor on a machine number 6 Rectifier Device (RD) model that is the chamfer griding machine located in the specified sector, to monitor the electric current of the specific motor shown in Figure 4 (drag rectification engine) during operations or inactivity.

The PoC entailed a detailed study of machine locations, considering distances and the feasibility of wiring. A wireless sensor network was chosen due to the impracticality of wiring in the environment. The necessary RSSI variations also proved crucial in monitoring operator movement during different shifts: four operators from 7:00 AM to 5:30 PM, two from 5:30 PM to 9:30 PM, and four again from 9:30 PM to 6:20 AM.

MOTIVATION 1 – MONITORING MACHINE CYCLES

The current measurement was conducted using a 10A current sensor on the specific AC motor of the RD6 machine, connected to the analog ports of the ATMEGA controller in the radio device. Figure 3 illustrates the RD6 machine and the rectified piece.

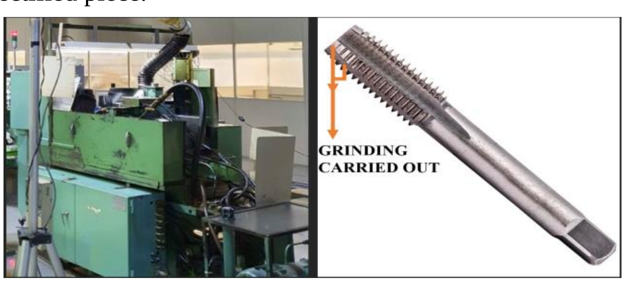

Figure 3. RD6 Machine and Rectified chamfered piece.

The radio device's firmware was configured to detect current values and transmit them in packets through the wireless sensor network [12] [14] [15].

Figure 4 illustrates the process of current measurement and the connection to the WSN up to the "Sensor Base" [11] (an edge element in Layer 3 of the TpM). This base receives machine data and forwards it to a computer in the factory office (Layers 4, 5, and 6 in the TpM) using a physical USB connection via an RJ45 CAT5 Ethernet cable, as depicted in Figure 5 from Motivation 2. Other devices within the WSN serve as sensor nodes, retransmitting the signal.

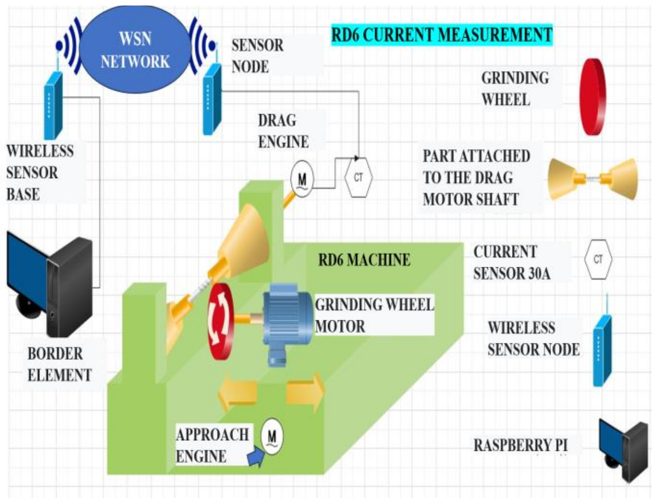

Figure 4. RD6 Current Measurement.

From Figure 4, it is noteworthy noting that the RD6 machine comprises three distinct AC motors. The first motor controls the platform's movement, the second one maintains continuous rotation of a grinding wheel, and the third one, known as the 'drag motor,' is activated by the operator after inserting the piece to be rectified.

The measurement of current in the drag motor is critical in determining whether the machine is operational or stopped. During operation, the drag motor consumes between 1 and 1.5 A for approximately 30 seconds when used for grinding a piece. After this interval, the motor no longer consumes current (0 A).

MOTIVATION 2 – RSSI MEASUREMENT TO DETECT OPERATOR'S MOVEMENT IN THE AREA.

A wireless sensor network was used to monitor the operators' movement in the chamfer grinding sector by analyzing variations in movement through RSSI. Figure 5 provides a detailed view of the network and showcases the "things" of the associated IoT solution.

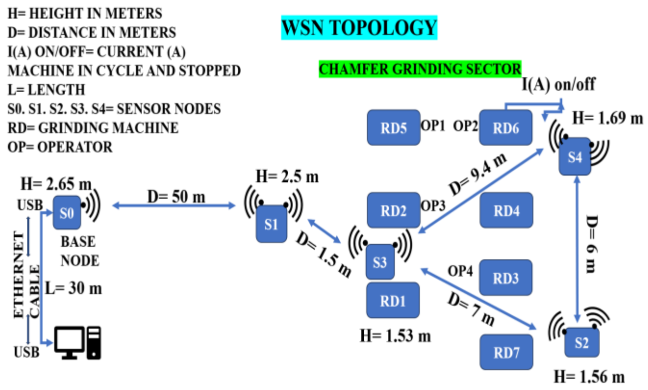

Figure 5. WSN topology.

The topology of a WSN defines the distances and heights of the sensor nodes, illustrating the propagation environment from the base station to the sensor nodes.

Before continuing with the PoC, it is necessary to collect all necessary information regarding production environments of the specified sector including routines, machines work type and specific rules. Meetings with designated specialists and understanding of business rules aligned with the things can define the bases of the PoC deployment.

b) Business Rules

The current scenario involves understanding production performance and management, emphasizing the lack of real-time monitoring in production. There is a need to supervise both machines and operators, and it is crucial for the IIoT solution to be non-intrusive to avoid disrupting production.

c) Specialist

The designated company expert engineers of the production plant explained the operation of the machines and their components. A study identified relevant parameters and a suitable sector for prototyping. The parameters to be collected and the best approach for the IIoT solution were defined.

d) Things

Details about the location, machinery, and processes were provided. The chamfer grinding sector, being the oldest in the company, was chosen for the Proof of Concept. After being approved at the enterprise level, the PoC was implemented in the factory through connected devices.

2) PHASE 2: REQUIREMENTS

a) Level 6 Exibition

Methods were established to quantify and display data for the enterprise level, including RD6 machine operation cycles, idle times, and personnel movement with 4 and 2 operators during different shifts.

b) Level 5 Abstraction

During two-and-a-half-hour measurements intervals in each shift, algorithms analyzed the collected digital data and presented it graphically.

c) Level 4 Storage

For the execution of the PoC, which took place after processing, the files stored the raw data from machine cycles and operator activity.

d) Level 3 Edge Element

Edge component responsible for collecting raw data during the testing period.

e) Level 2 Connectivity

Data transmission takes place through a wireless sensor network due to the absence of wiring in the environment. RSSI variation is crucial for monitoring operators across different shifts. The shifts are as follows: 4 operators from 7:00 AM to 5:30 PM, 2 operators from 5:30 PM to 9:30 PM, and 4 operators from 9:30 PM to 6:20 AM.

f) Level 1 Local Node / Sensing

The key parameters to be measured are the current of the motor in the machine during movement or idle states, and the variations in RSSI to monitor the number of operators in the sector.

3) PHASE 3 IMPLEMENTATION

During implementation, a framework is utilized, aligned with the technology, to define the elements according to the reference model [8].

a) Level 1 Local Node

In WSN, a node on the RD6 machine includes a current sensor and an S4 sensor for data transmission. The current is measured by a sensor capable of up to 10 A, connected to the RD6's drag AC motor and the ATMEGA controller of the radio device.

The firmware of the radio device has been adjusted to transmit the current values over the wireless network. Figure 4 illustrates the process up to the sensor base. This base receives and forwards the data to a computer in the factory office through USB connections and an RJ45 CAT5 Ethernet cable.

b) Level 2 Connectivity

The radio sensor devices, internally developed by the WISSTEK/Unicamp lab, operate at 915 MHz with 2-FSK modulation and 125 kHz channels. They feature an RF module with an integrated microcontroller, transceiver, and RF amplifier, achieving a transmission power of up to 500mW (27 dBm).

The devices were configured to operate on channel 4 (915-928 MHz) with a power of 5 dBm (31mW). RSSI and current measurements were collected during shifts with 4 and 2 operators, totaling approximately 2 and a half hours measurement per shift. The data, including RSSI and current, is sent to the base node and processed on the computer.

The RSSI measurements are recorded and graphically analyzed in LOG_TXT files, with received power values from the sensor nodes (in dBm) in the LOG_RSSI_TXT file. Routes configured with multiple hops generate noticeable RSSI variation based on the movement of operators in the sector. Figure 6 illustrates the WSN topology with the specification of hops for each route.

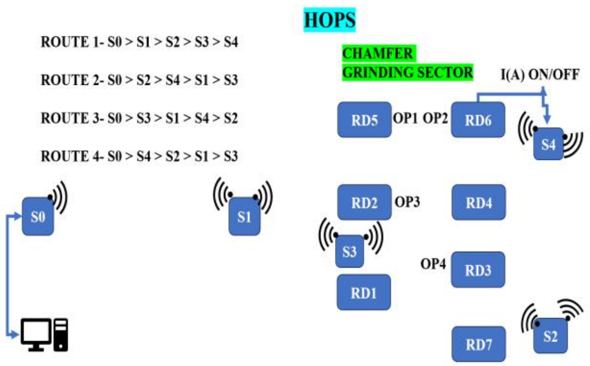

Figure 6. Hops.

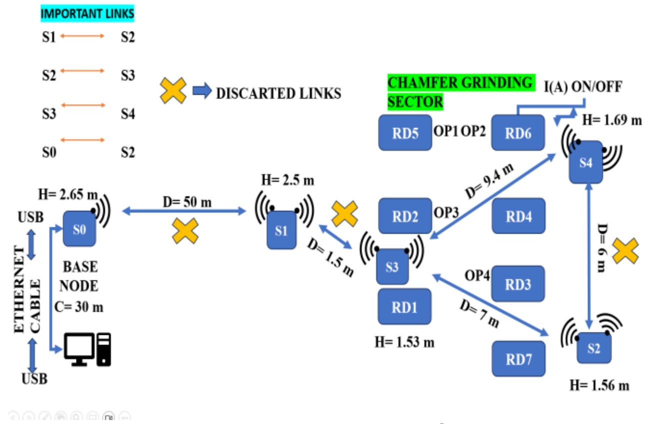

Figure 7. Important Links.

c) Level 3 Edge

A Raspberry Pi computer was installed and connected to the base node to store and display the data. Current values were collected, converted into packets, and subsequently processed at the edge element. At this element, thresholds were configured to differentiate between the machine's operating cycle (ON) and the stopped state (OFF) based on the current values. Current measurements stay within the established thresholds, corresponding to the machine's operating cycle, with values ranging from 1.0 A to 1.6 A.

d) Level 4 Storage

On the Raspberry Pi, the data is stored in CSV-compatible formats for later conversion in Excel.

e) Level 5 Abstraction

The raw data collected by the edge element was processed through algorithms and analyzed in Excel.

f) Level 6 Exibition

Illustrates the collected data with graphics and statistics analysis.

V. RESULT ANALYSIS

A. RSSI

For the analysis of RSSI variation results, we considered only the links that were physically installed, traversing the production sector. These links are more susceptible to RSSI variations due to operator movement.

Based on the measurement logs, we could observe the correlation between the line-of-sight location of the link and the RSSI variations, resulting in a more realistic scenario. Figure 7 shows the relevant links for analysis, selected from the result records, excluding irrelevant links.

Figure 8 shows the RSSI measurement over time in two distinct scenarios: when 4 and 2 operators were close to the machines.

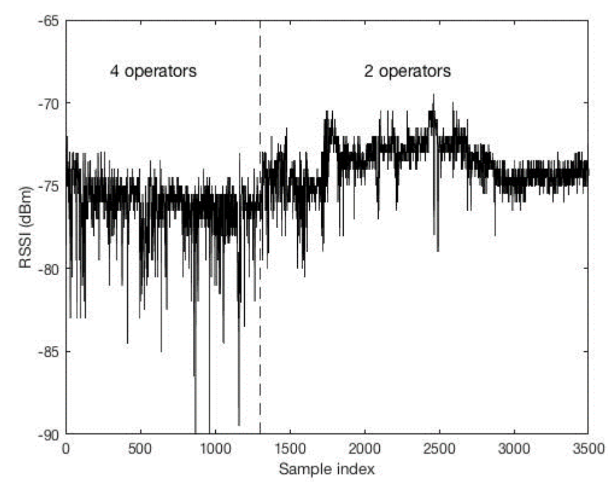

Figure 8. RSSI Variations.

It is clear, from this figure, that the level of RSSI variation is affected by the number of nearby operators.

To quantify the level of RSSI variation, we calculated the standard deviation of the RSSI measurements over a window of *L* = 100 measurements, using equation (1)

$$V(k) = \sqrt{\frac{1}{L-1}\sum_{i=k}^{i=k-L+1}[T(i) - \mu(k)]^2} \quad (1)$$

where L is the window length and T(i) are the RSSI measurements. The quantity μ(k) is the mean RSSI calculated as the equation (2)

$$\mu(k) = \sum_{i=k}^{i=k-L+1}\frac{T(i)}{L} \quad (2)$$

Figure 9 displays the standard deviation with 4 and 2 operators.

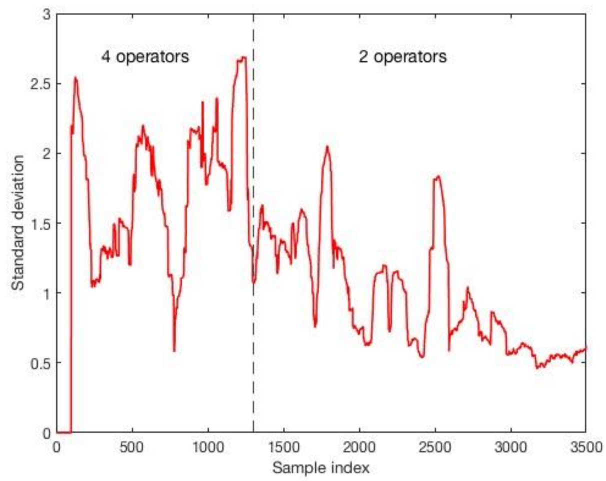

Figure 9. Std deviation.

This figure clearly shows that the standard deviation tends to be higher when there are more operators close to the machine, indication that RSSI measurements can be used to monitor operator's movement.

B. *RD6 Machine Current Measurement*

A pie chart illustrates the active and inactive time ratio and ON and OFF cycles in Figure 10. Figure 11 displays the measurement of motor current during operation and at rest in a zoom view.

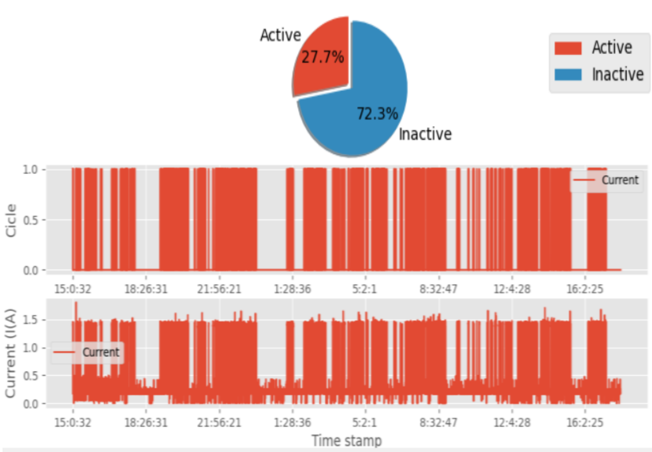

Figure 10 - Cycle ON OFF.

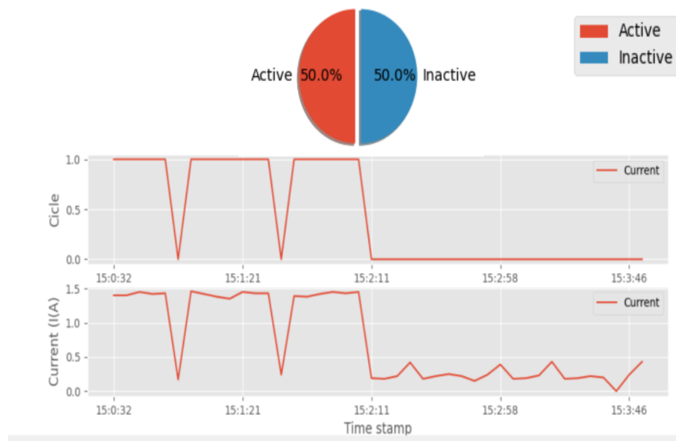

Figure 11. ON OFF ZOOM.

VI. CONCLUSION

Retrofit 4.0 followed the principles of the production system and the reference model, adopting TpM at every stage. The method played a pivotal role in shaping the IIoT solution, from understanding the business to implementing the proof of concept. The PoC met the expectations of the enterprise sector, demonstrating the effectiveness of the solution at the factory level.

The results of the PoC described the industrial environment, serving as a baseline for comparing variations in production performance and identifying gaps. The RSSI measurements revealed sector movement more clearly in the curve with four operators compared to that with two. RSSI variations can be used to interpret different patterns of human movement.

The monitoring of the RD6 machine's motor current demonstrated effectiveness in tracking the "ON" and "OFF" states. This allows real-time recording of production performance, indicating rework, production adjustments, and technical improvements. Both RSSI and current have proven to be powerful tools for productive management within the context of Industry 4.0.

The TpM application for Retrofit 4.0 through PoC proved effective contributing to a non-invasive transition process for legacy industrial plant and shown various possibilities of KPI´s management, like control machine work cycle and personal behavior in our study case, narrowing control gap which is reflected on production performance data.

ACKNOWLEDGEMENTS

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001, and by Conselho Nacional de Desenvolvimento Científico e Tecnológico - Brazil, Grant 313213/2021-6.

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